

The NOAA Climate Reanalysis Task Force: Activities and Examples from Stratospheric Ozone and the Pacific Walker Circulation

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Task Force mission:

Address outstanding issues in atmospheric, oceanic, and
land reanalysis

Develop a greater degree of integration among Earth system
reanalysis components.

Integrate with national and international efforts.

Leads: Arun Kumar, Gilbert Compo; co Leads: James Carton, Michael Ek

Organized by CPO— Modeling, Analysis, Predictions, and Projections

[http://cpo.noaa.gov/ClimatePrograms/
ModelingAnalysisPredictionsandProjections/MAPPTaskForces/
ClimateReanalysisTaskForce.aspx](http://cpo.noaa.gov/ClimatePrograms/ModelingAnalysisPredictionsandProjections/MAPPTaskForces/ClimateReanalysisTaskForce.aspx)

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Projects

Research towards the next generation of NOAA Climate Reanalyses

PI: Arun Kumar [Next Presentation]

Improving the Land Surface Components of the CFS Reanalysis

PI: Michael Ek

Exploration of advanced ocean data assimilation schemes at NCEP

PI: James Carton

Improving the Prognostic Ozone Parameterization in the NCEP GFS and CFS for Climate Reanalysis and Operational Forecasts

PI: Gilbert Compo [Described here]

Strategies to Improve Stratospheric Processes in Climate Reanalysis

PI: Craig Long

Evaluating CFSR Air-Sea Heat, Freshwater, and Momentum Fluxes in the context of the Global Energy and Freshwater Budgets

PI: Lisan Yu

Diagnosing and quantifying uncertainties of the reanalyzed clouds, precipitation and radiation budgets over the Arctic and Southern Great Plains using combined surface-satellite observations

PI: Xiquan Dong

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Improve Reanalysis Components in

PI: Michael Ek

Atmosphere, Land, and Ocean

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Improve Stratosphere

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Diagnoses to evaluate and speed

Diagnosing and quantifying the reanalyzed clouds, precipitation and radiation budgets over the Arctic and Southern Great Plains using combined surface-satellite observations

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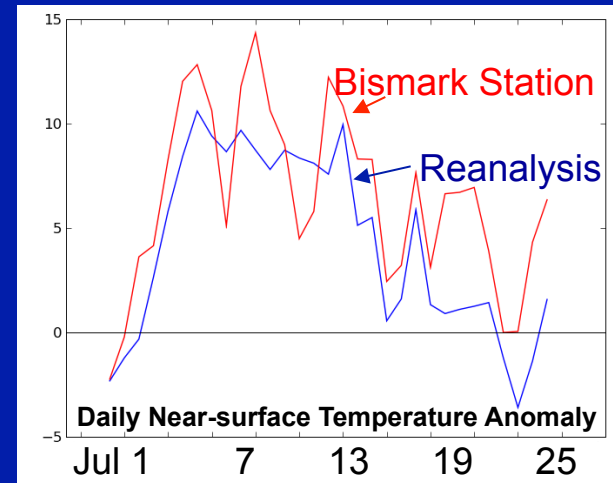
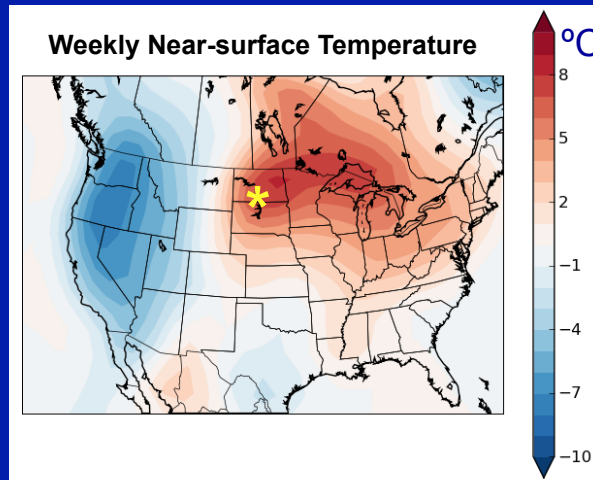
Improvements

The 20th Century Reanalysis Project (1871-2011)

Summary: An international project led by NOAA and CIRES to produce *4-dimensional* reanalysis datasets for climate applications extending back to the 19th century using an Ensemble Kalman Filter and *only surface pressure observations*. Research will lead to improved historical reanalysis back to 1850, part of suite of NOAA Climate Reanalyses.

Weekly-averaged anomaly during **July 1936** United States Heat Wave (997 dead during 10-day span)

Daily variations compare well with in-situ data.



The reanalyses provide:

- First-ever estimates of near-surface to tropopause 6-hourly fields extending back to the beginning of the 20th century;
- Estimates of uncertainties in the basic reanalyses and derived quantities (e.g., storm tracks).

Examples of uses:

- Validating climate models.
- Determining storminess and storm track variations over the last 150 years.
- Understanding historical climate variations (e.g., Pacific Walker Circulation).
- Estimating risks of extreme events



Improving the Prognostic Ozone Parameterization in the NCEP GFS and CFS for Climate Reanalysis and Operational Forecasts

PI: Gilbert P. Compo^{1,2}
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³NOAA, National Centers for Environmental Prediction, Climate Prediction Center

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⁵Naval Research Laboratory

⁶University of Bern

Naval Research Laboratory

CHEM2D Ozone Photochemistry Parameterization

(CHEM2D-OPP, [McCormack et al. \(2006\)](#))

CHEM2D-OPP is based on gas-phase chemistry circa 2000.
Same approach as used in ECMWF IFS (*Cariolle and Deque 1986*).
Includes ozone depletion from CFCs.

Net ozone photochemical tendency
functional form of Production P minus Loss L

$$\frac{d\chi_{O_3}}{dt} = (P - L) [\chi_{O_3}, T, c_{O_3}]$$

Approximate as Taylor series linearized about
reference state (denoted by overbar).

$$\frac{\partial \chi}{\partial t} (P - L) = (P - L)_0 + \left. \frac{\partial (P - L)}{\partial \chi_{O_3}} \right|_0 (\chi_{O_3} - \bar{\chi}_{O_3}) + \left. \frac{\partial (P - L)}{\partial T} \right|_0 (T - \bar{T}) + \left. \frac{\partial (P - L)}{\partial c_{O_3}} \right|_0 (c_{O_3} - \bar{c}_{O_3})$$

χ_{O_3} prognostic Ozone mixing ratio

T Temperature

c_{O_3} column ozone

Partial use of CHEM2D-OPP in the current NCEP Global Forecast System (GFS) atmosphere/land model

$$\frac{\partial \chi}{\partial t}(P-L) = (P-L)_0 + \frac{\partial(P-L)}{\partial \chi_{O_3}} \bigg|_0 (\chi_{O_3} - \bar{\chi}_{O_3})$$

Reference tendency $(P-L)_0$ and all partial derivatives are computed from odd oxygen ($Ox \equiv O_3 + O$) reaction rates in the CHEM2D photochemical transport model.

CHEM2D is a global model extending from the surface to ~120 km that solves 280 chemical reactions for 100 different species within a transformed Eulerian mean framework with fully interactive radiative heating and dynamics.

The partial CHEM2D-OPP is used in the 20th Century Reanalysis (20CR) and operational NCEP forecast system, and atmosphere of Climate Forecast System (CFS) Reanalysis (CFSR) and operational CFSv2.

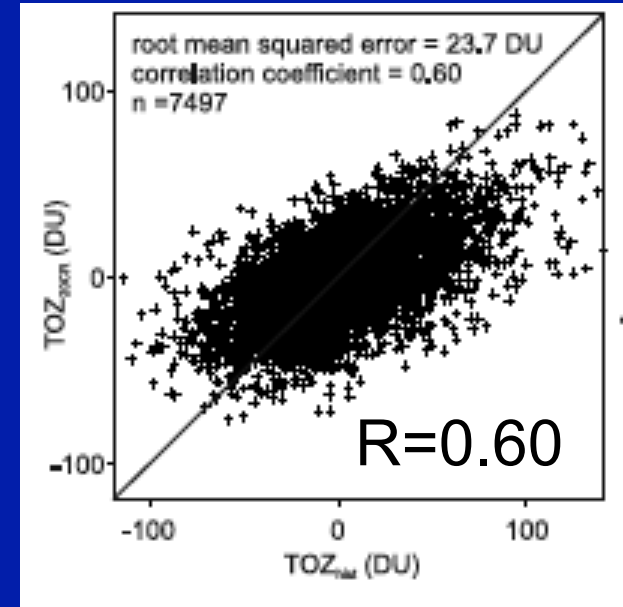
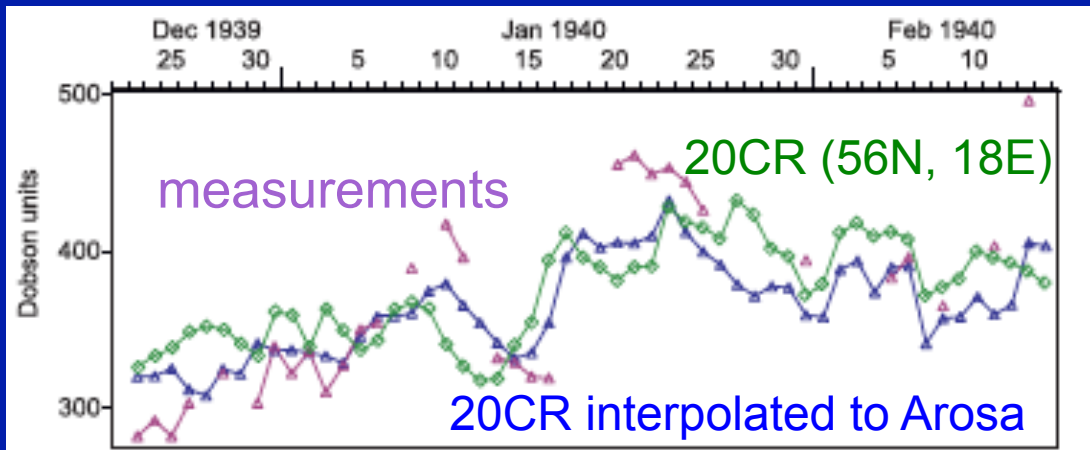
χ_{O_3} prognostic Ozone mixing ratio
 T Temperature
 c_{O_3} column ozone

Daily column ozone measurements and 20CR daily ozone at Arosa, Switzerland (46.8N, 9.7E)

Anomaly comparison
spanning 1924 to 1963

Dec 1939

Feb 1940



20CR ozone field has large scale fluctuations that reflect ozone highs associated with, e.g., cold air outbreaks. Overall, find high correlations in Northern Hemisphere midlatitudes where dynamics are an important contributor to ozone variations. ([Brönnimann and Compo 2012](#)).

Issue: Reference state ozone, temperature, and CHEM2D-OPP parameterization coefficients include the chemistry arising from *CFCs throughout the 1871-2011* 20CR record.

Project: new CHEM2D-OPP coefficients and an appropriate ozone climatology will be generated for the period before widespread CFC usage.

Test effects on 20CR fields by comparing to historical ozone observations and to upper-air temperature observations.

Also include additional terms.

Is the Pacific Walker Circulation changing in response to Global Warming?

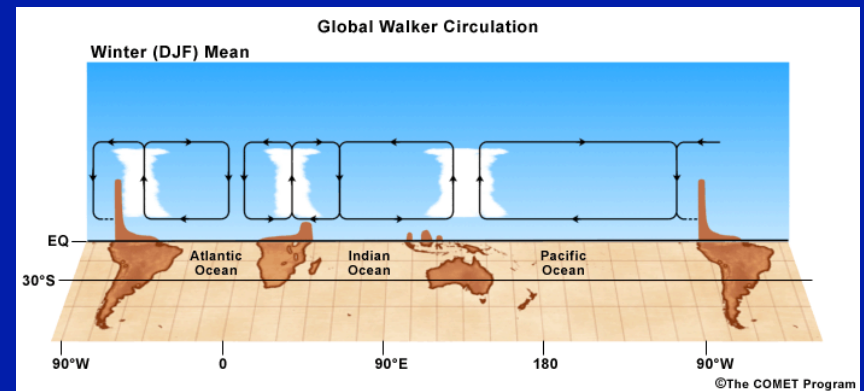
Results from Compo et al. 2011 (Q. J. Roy. Met. Soc.) and

Sandeep, Stordal, Sardeshmukh, and Compo 2014 (Cli. Dyn., in press, <http://dx.doi.org/10.1007/s00382-014-2135-3>)

Yes, PWC seems to be **strengthening in several observational datasets.**

Yes, PWC seems to be **weakening in coupled model simulations.**

Walker Circulation is the east-west part of the global overturning circulation.



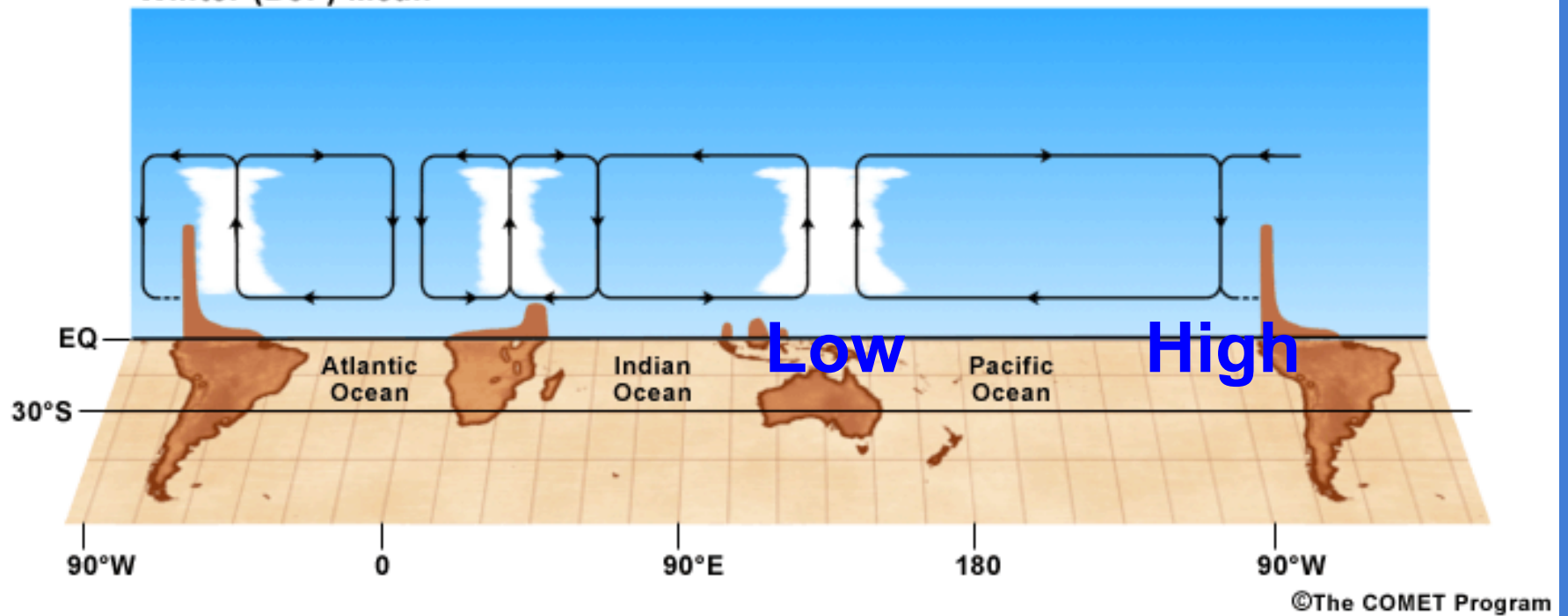
As global temperature increases,
global water vapor increases faster than precipitation in
coupled climate models forced with greenhouse gases.

Overturning circulation (global convective mass flux)
must **weaken** to compensate [*Held and Soden 2006*].

- Sea Level Pressure-based Pacific Walker Circulation used
as proxy to investigate:
Vecchi et al. 2006 and others found **weakening**.
Meng et al. 2012 and others found **strengthening**.
Solomon and Newman 2012 found **no change**.

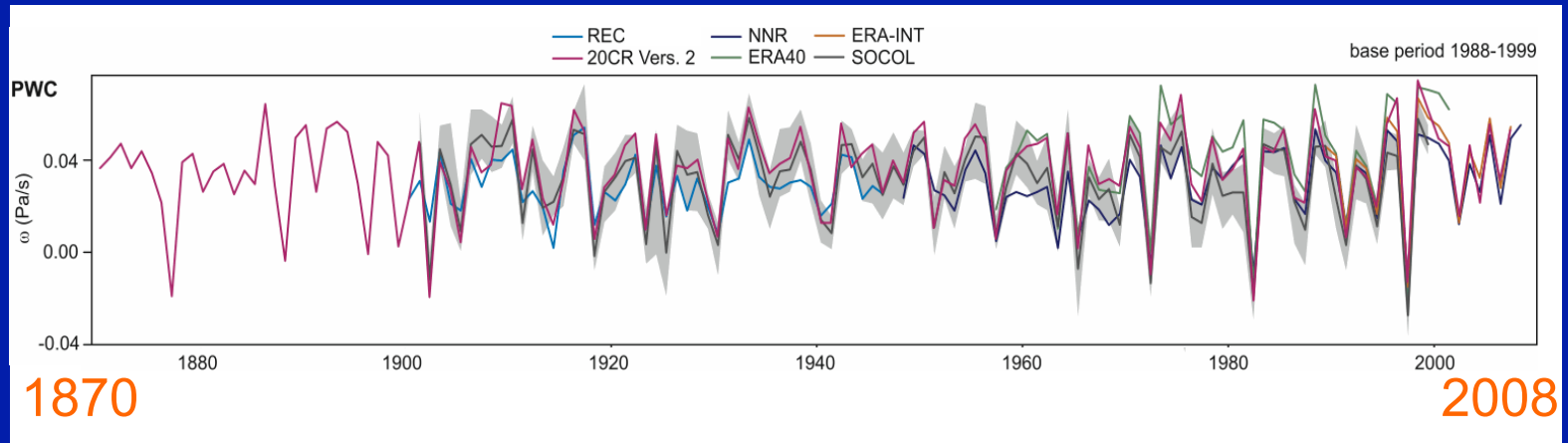
Global Walker Circulation

Winter (DJF) Mean

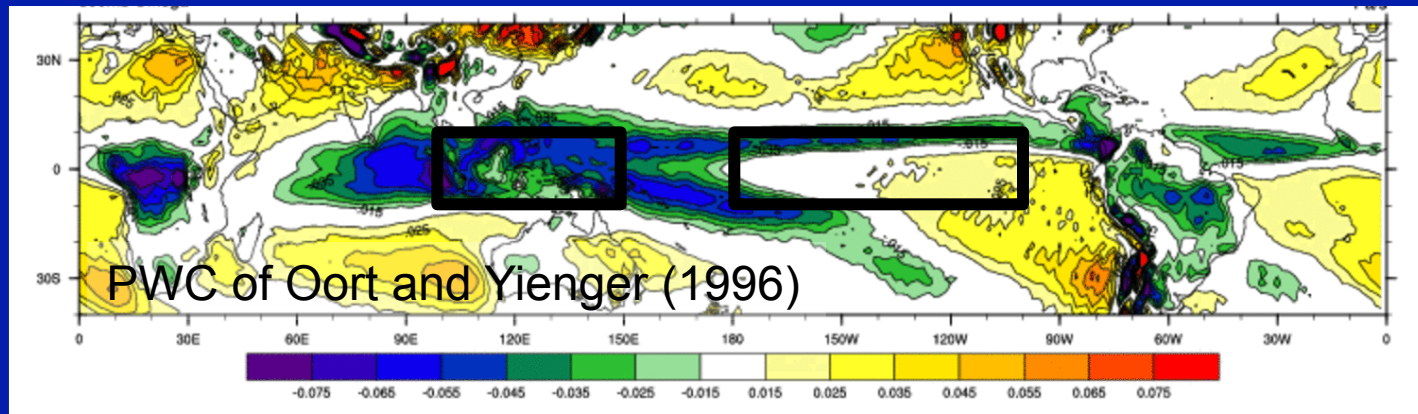


Pacific Walker Circulation from Statistical Reconstructions, AGCM integrations, and 20th Century (20CR), ERA-40, NCEP-NCAR, ERA-Interim Reanalyses.

500 hPa
vertical
velocity,
SONDJ



Climo
(ERA-Int)



Agreement in overturning PWC:

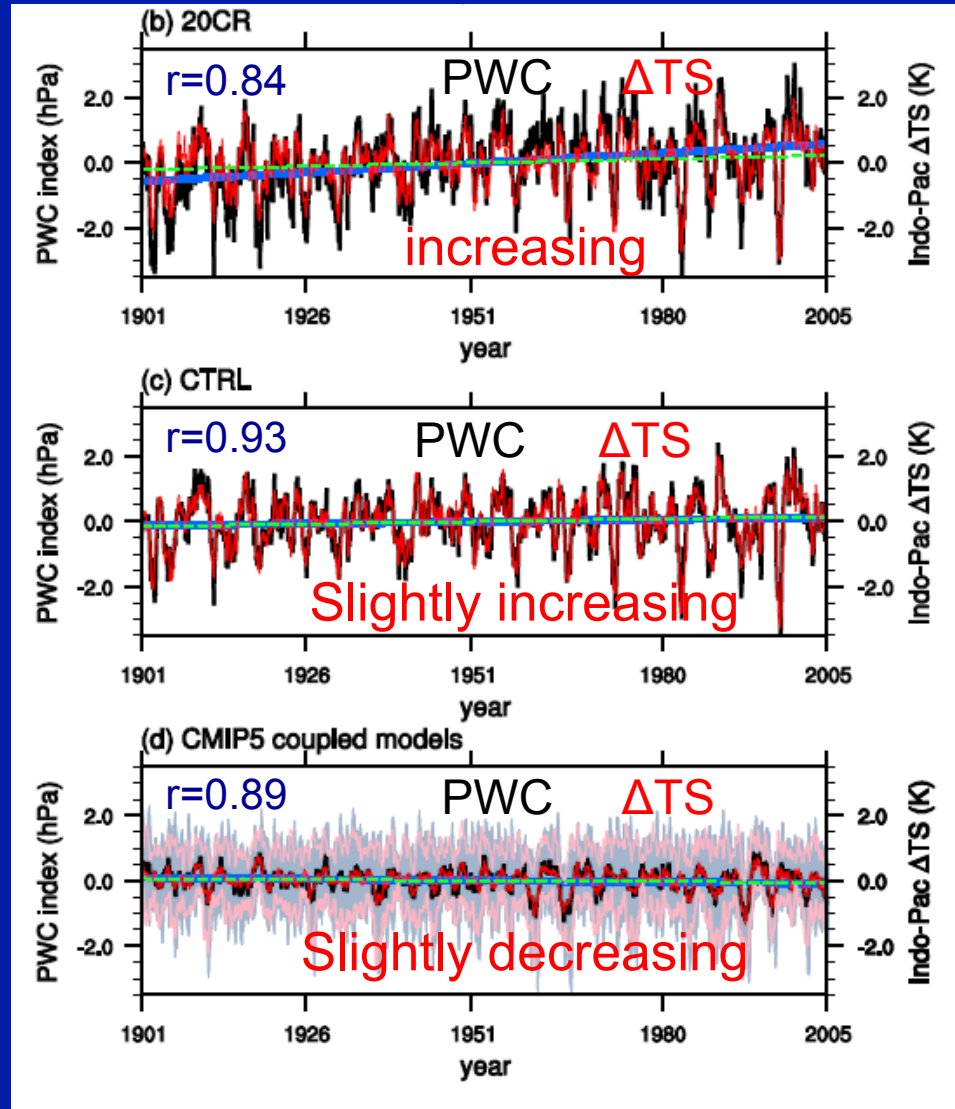
correlations between ERA-40 and 20CR > 0.95.

No significant trend in PWC since 1871 using pressure-based 20CR.

Compo et al. 2011

Anomalies of SLP-based Pacific Walker Circulation **PWC** and West minus East Equatorial Pacific SST gradient **ΔTS**

20CR

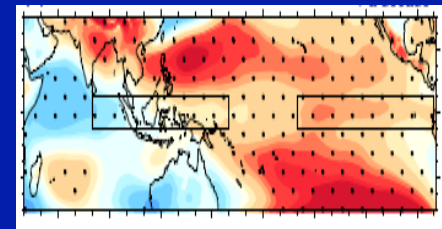


SST-forced CAM4
(3 members)

Radiative forcings
CMIP5
(12 models)

ΔTS from
HadISST1

ΔTS is
average of
HadISST1,
ERSSTv3b,
COBE1



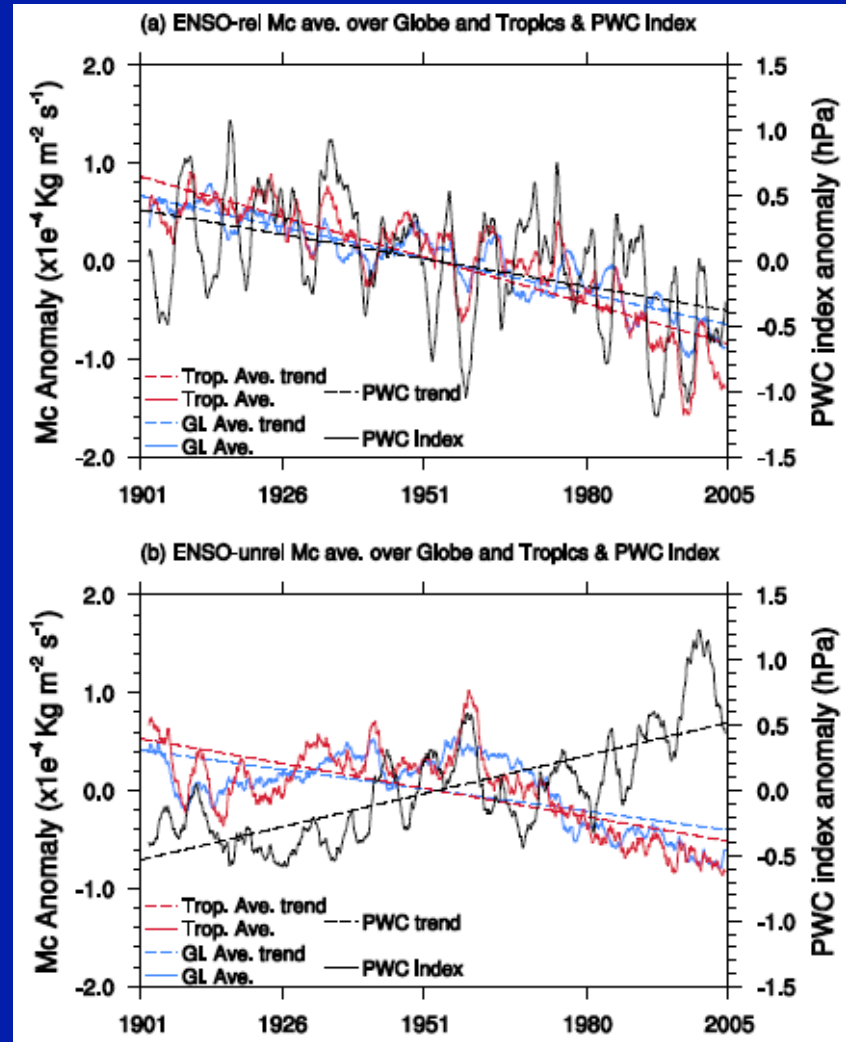
Sandeep et al. 2014

PWC trends and variability are closely related to ΔTS

PWC compared to convective mass flux (Mc) in ENSO-related and ENSO-unrelated SST-forced CAM4 simulations

SSTs filtered to
retain ENSO
(3 members)

SSTs filtered to
remove ENSO
(3 members)



(Pacific
SST gradient
 ΔTS
weakens)

— PWC
— Tropical Mc
— Global Mc

(Pacific
SST gradient
 ΔTS
strengthens)

Sandeep et al. 2014

Global convective mass flux decreases as globe warms regardless of whether Pacific Walker Circulation weakens or strengthens.

Conclusions

1. NOAA Climate Reanalysis Task Force is researching reanalysis improvements and outstanding issues. Two examples: stratospheric ozone and Pacific Walker circulation.
2. Gas phase stratospheric ozone parameterization used in NCEP GFS, 20CR, and CFSR can be improved to be time-aware (e.g., before CFCs) and account for additional chemistry.
3. Pacific Walker Circulation trends and variability depend on definition. SLP-based definition closely related to SST gradient; almost unrelated even to *Tropical* overturning circulation.
4. SLP-based PWC index is **not a proxy** for global or tropical convective mass flux. Global arguments cannot be applied to regional circulation.
5. PWC appears to be **strengthening** over past century in reanalyses and SST-forced AGCM simulations.
6. SST-forced AGCM and GHG-forced CMIP5 historical simulations agree that **global and tropical convective mass flux is weakening**.
6. Some Goals of Reanalysis: improve representation and reduce uncertainty of climate trends, such as global overturning circulation, and improve stratosphere.

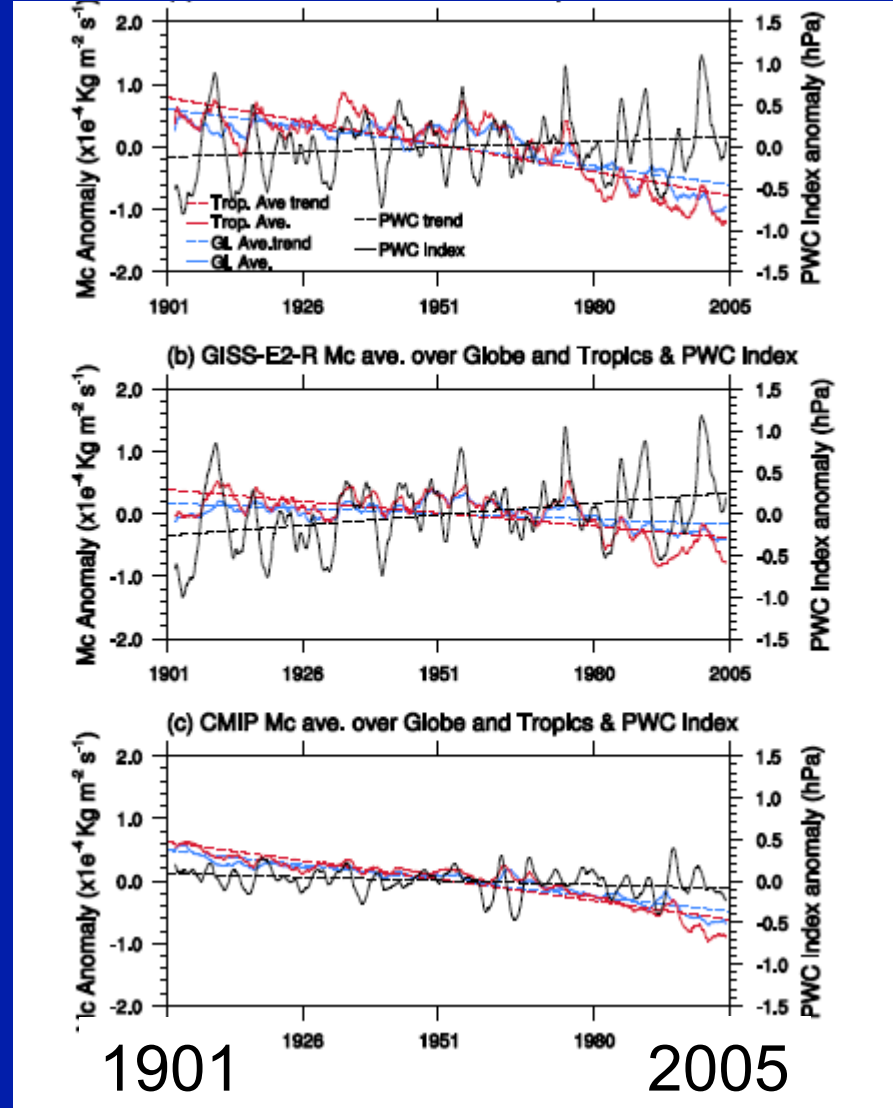
Extra Slides

Pacific Walker Circulation compared to Convective Mass Flux (Mc) from SST-forced and coupled GCMs

SST-forced CAM4
(3 members)

SST-forced
GISS-E2-R
(4 members)

Radiatively forced
CMIP5
(12 models)



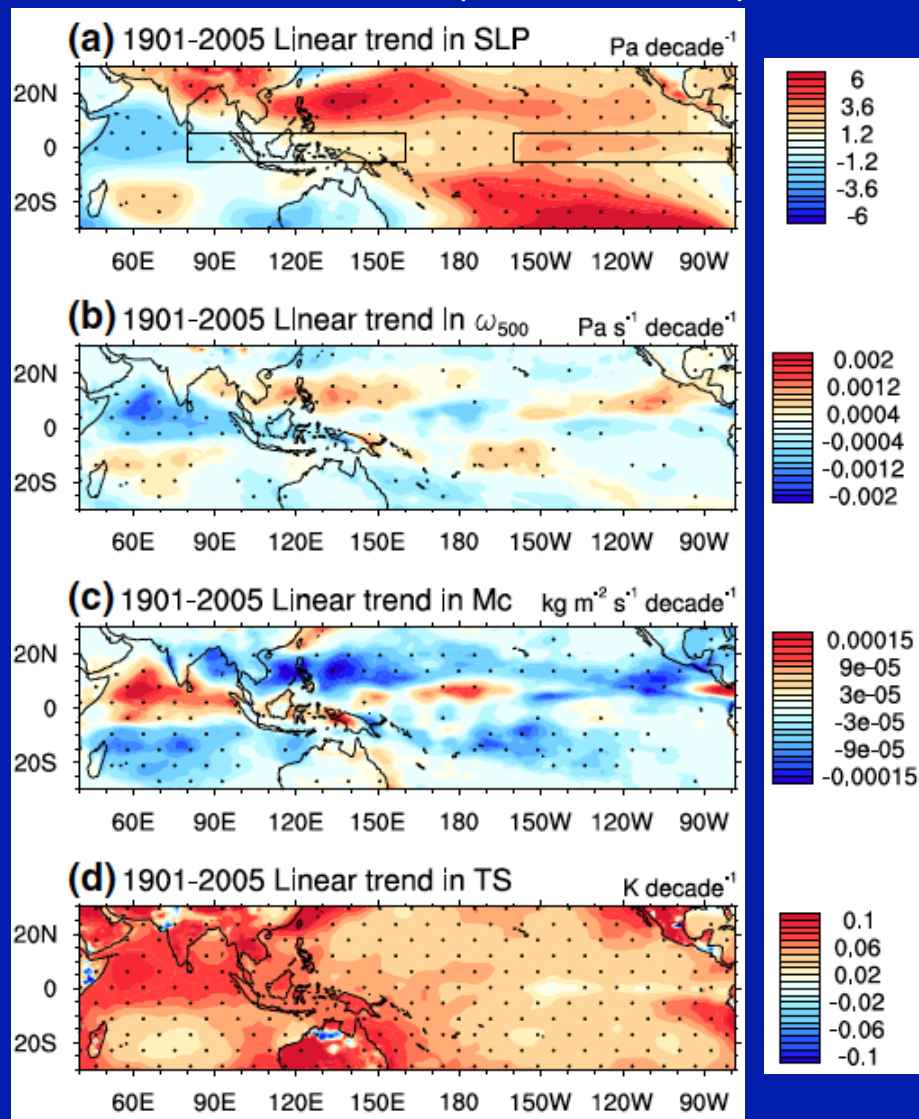
— PWC
— Tropical Mc
— Global Mc

Sandeep et al. 2014

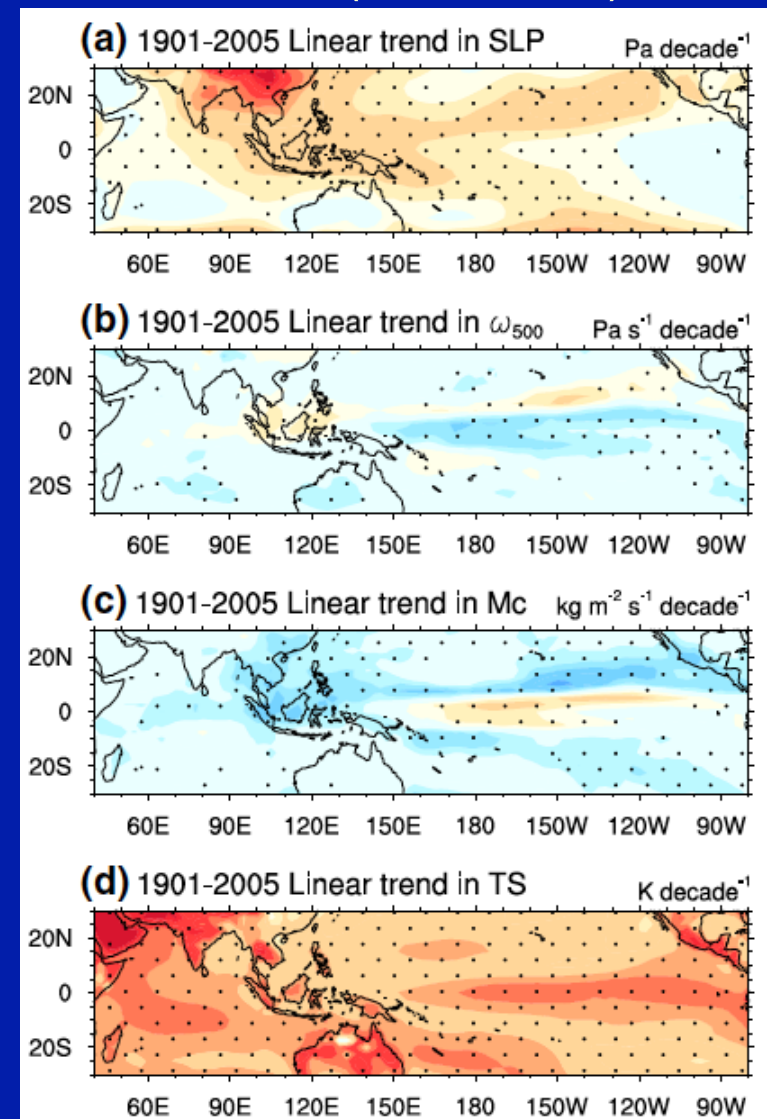
Correlation between Pacific Walker Circulation and convective mass flux is low for all simulations. Trends can be opposite.

SST and radiatively forced trends (1901-2005)

SST-forced CAM4 (3 members)

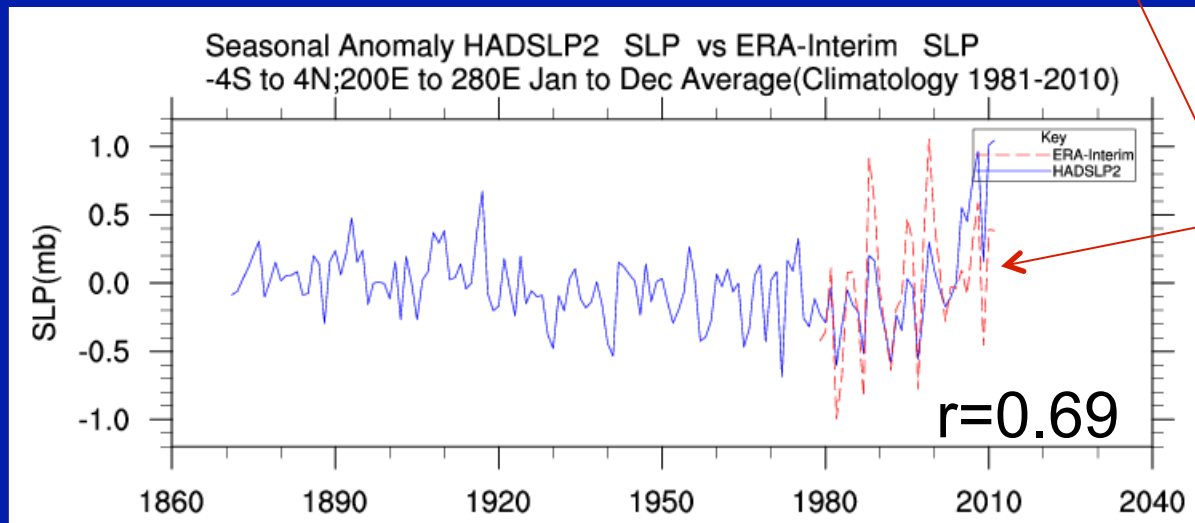
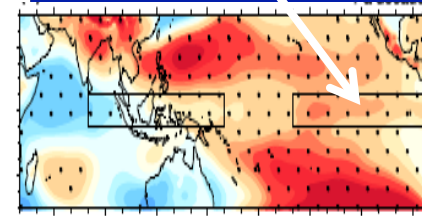
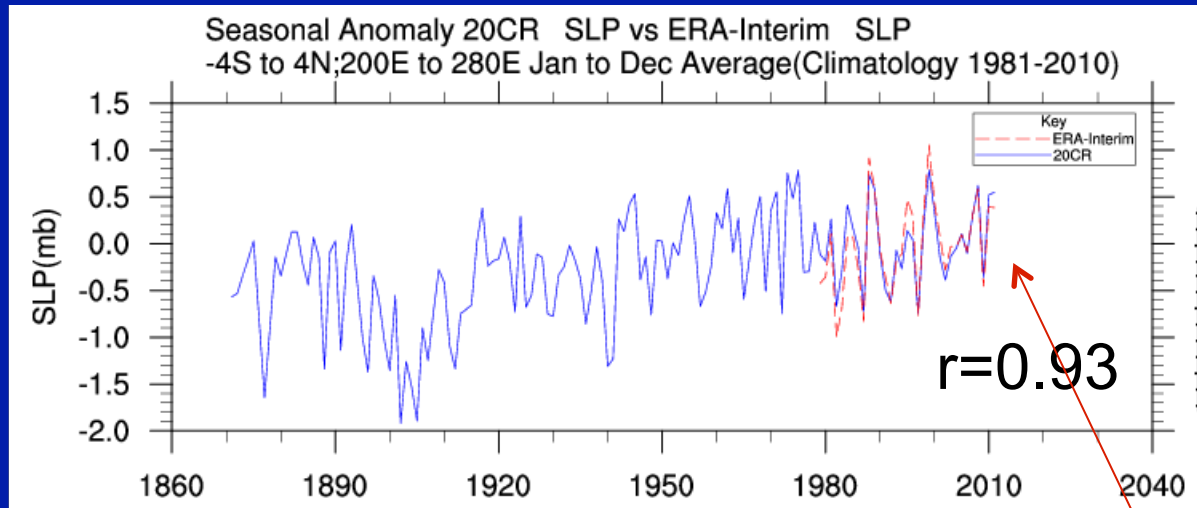


CMIP5 (12 models)



Different trends in various facets of Walker Circulation 20

Annual anomalies of Eastern box of SLP-based PWC

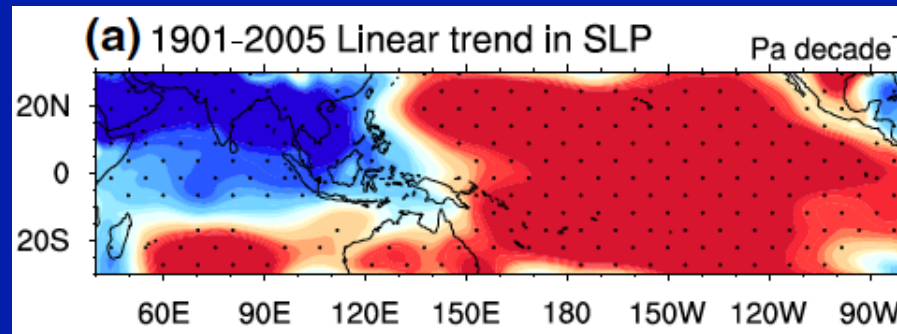


NOTE:
Change of
Scale!
ERA-Int
is the same
curve

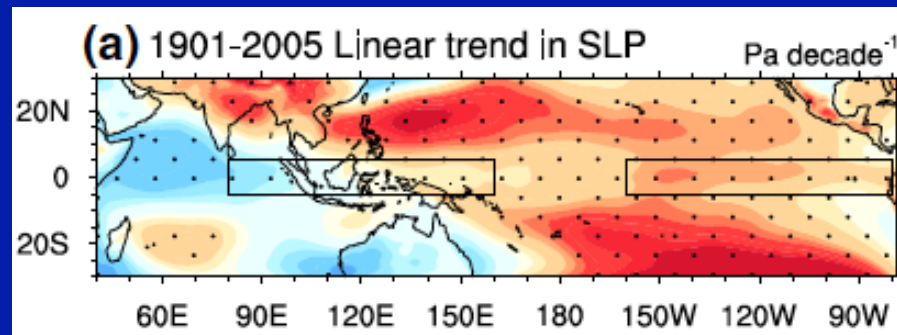
HadSLP2r has spurious increase after 2005 (becomes adjusted NCEP-NCAR reanalysis). Variance is consistently less than ERA-Int or 20CR. HadSLP2r correlation is lower with ERA-Int compared to 20CR.

Reanalysis, SST and radiatively forced trends (1901-2005)

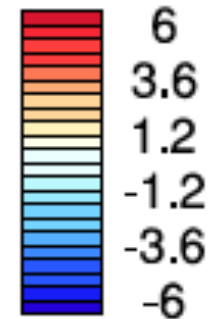
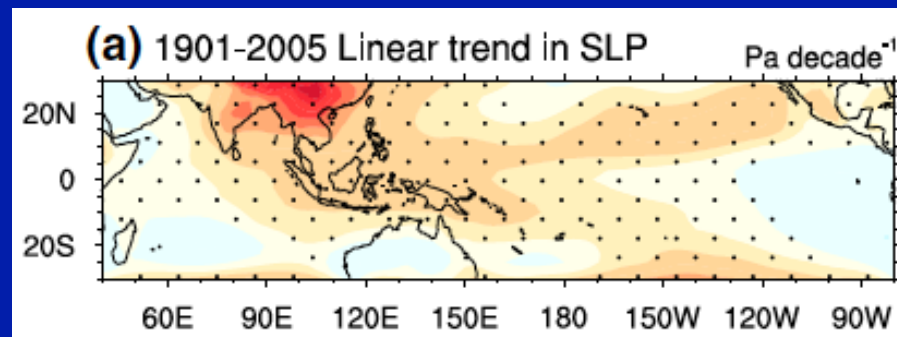
20th Century
Reanalysis 20CR



SST-forced CAM4
(3 members)



Radiatively forced
CMIP5
(12 models)

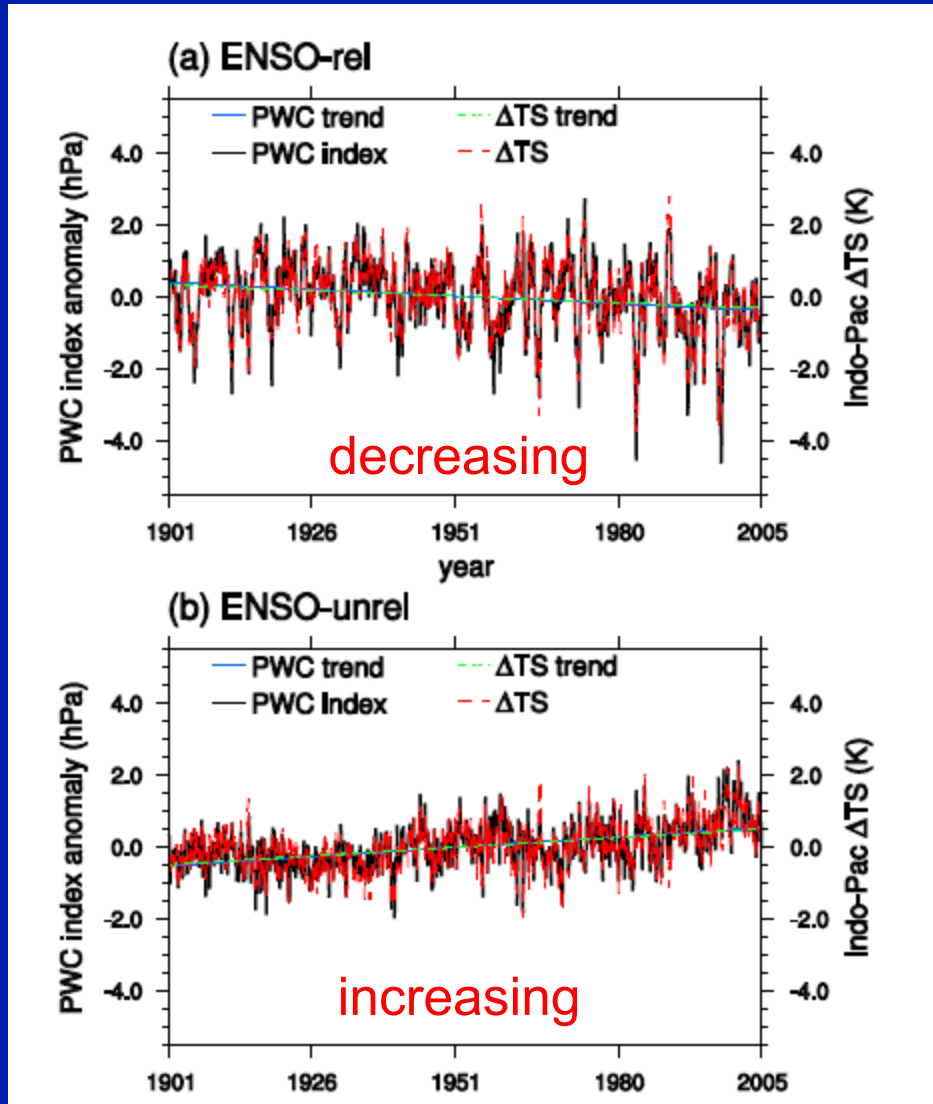


20CR trends agree better with SST-forced ensemble.
What is 20CR trend sensitivity to SST boundary condition?

CAM4 AGCM simulations forced by ENSO-related and ENSO-unrelated SSTs (filter from *Compo and Sardeshmukh 2010*)

SSTs filtered to
retain ENSO
(3 members)

SSTs filtered to
remove ENSO
(3 members)

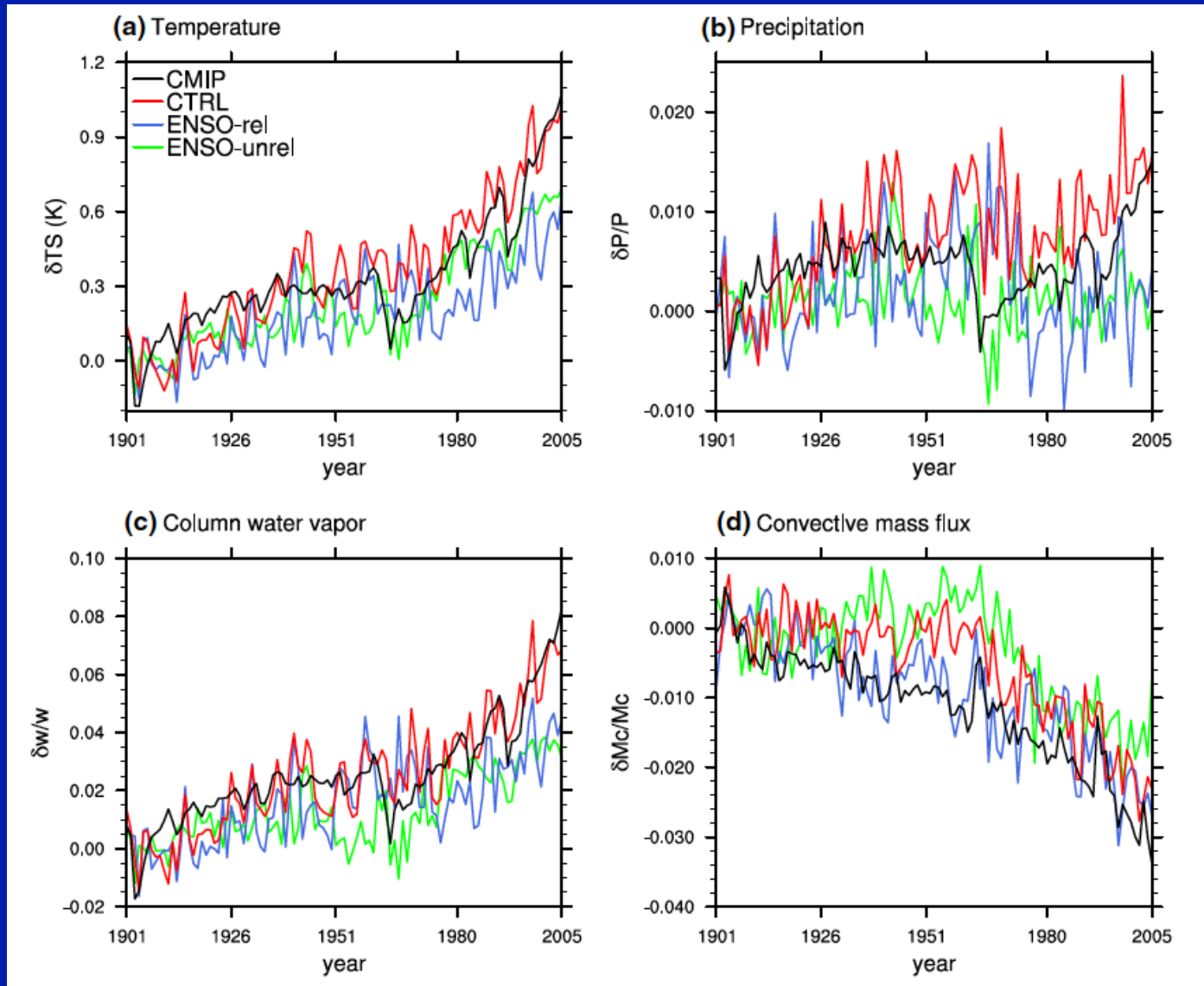


ΔTS is
average of
HadISST,
ERSSTv3b,C
OBE

Sandeep et al. 2014

Opposite SST gradient trends (ΔTS) force opposite PWC trends.

Change relative to 1901 to 1910 mean



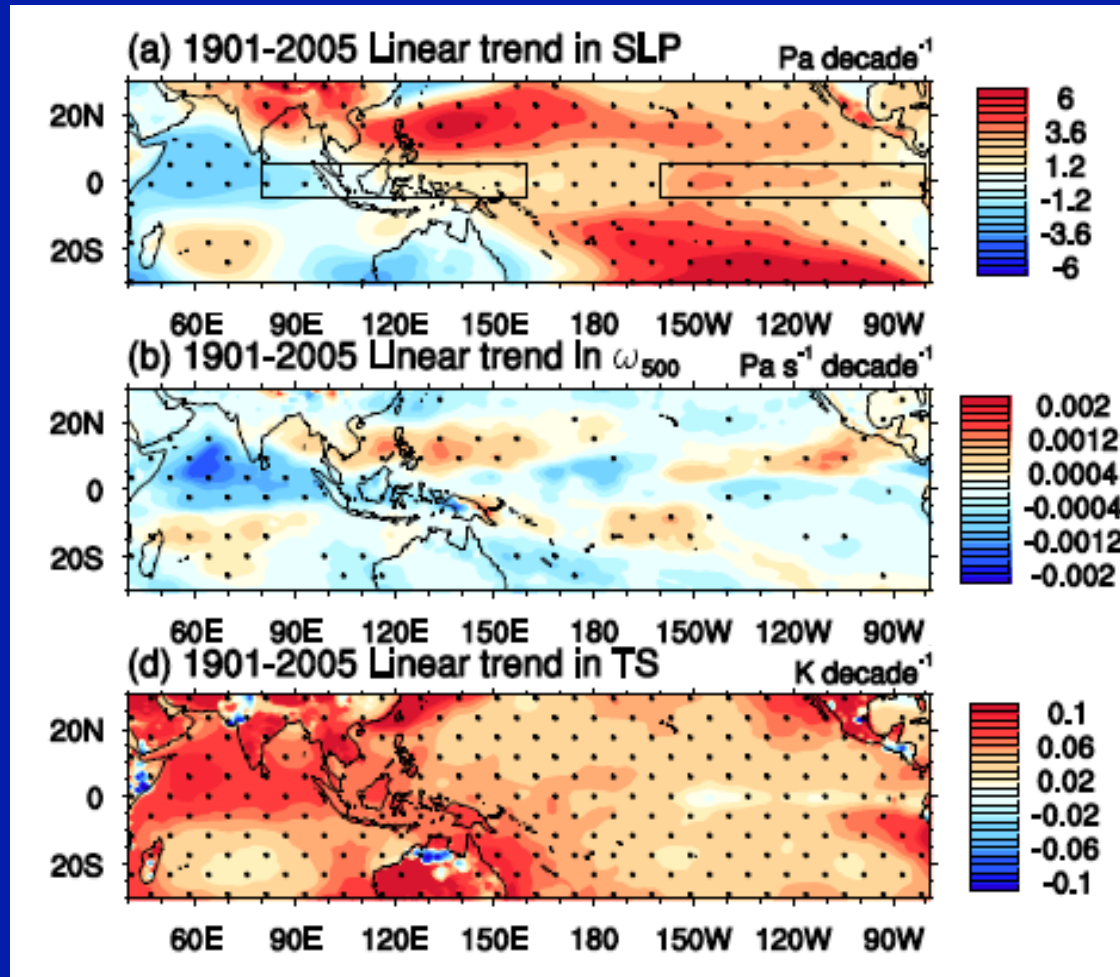
Sandeep et al. 2014

1901-2005 Linear Trend from CAM4 SST-forced simulations (3 ensemble members)

Sea
Level
Pressure

500 hPa
vertical
velocity

Land and
Sea Surface
Temperature



Each ensemble member has different SST dataset prescribed.

Average of HadISST1, ERSSTv3b, COBE SST

Sandeep et al. 2014

Trend patterns of SLP and vertical velocity correlate moderately ($r=0.41$).

Stratospheric Ozone

- A key radiatively active constituent in both solar and infrared radiation
- Affects temperature of stratosphere, troposphere, and surface
- Reduces harmful ultraviolet light reaching surface
- Ozone variations play role in climate variability of Northern and Southern Hemisphere
- Reanalysis systems, and the weather models on which they rely, must accurately represent the ozone field and its effect on climate variations.
- Complete ozone photochemistry is too computationally intensive to include in current weather and climate models
- So, parameterize processes!

Ensemble Filter Algorithm (Whitaker and Hamill, 2002)

Ensemble mean

$$\bar{\mathbf{x}}_j^a = \bar{\mathbf{x}}_j^b + \mathbf{K} \left(y^o - \bar{y}_j^b \right),$$

Ensemble deviations

$$\mathbf{x}_j'^a = \mathbf{x}_j'^b - \tilde{\mathbf{K}} \left(y_j'^b \right),$$

Sample
Kalman
Gain

$$\begin{aligned} \mathbf{K} &= \mathbf{P}^b \mathbf{H}^T (\mathbf{H} \mathbf{P}^b \mathbf{H}^T + R)^{-1} \\ &= \frac{1}{n-1} \sum_{j=1}^n \mathbf{x}_j'^b y_j'^b \left(\frac{1}{n-1} \sum_{j=1}^n y_j'^b y_j'^b + R \right)^{-1} \end{aligned}$$

Sample
Modified
Kalman Gain

$$\tilde{\mathbf{K}} = \left(1 + \sqrt{\frac{R}{\mathbf{H} \mathbf{P}^b \mathbf{H}^T + R}} \right)^{-1} \mathbf{K},$$

$\mathbf{x}_j = \bar{\mathbf{x}} + \mathbf{x}'_j$ is pressure, air temperature, winds, humidity, etc. at all levels and gridpoints, every six hours.

y^o is only observations of hourly and synoptic surface pressure,

$\mathbf{y}^b = \mathbf{H} \mathbf{x}^b$ is guess surface pressure

20th Century Reanalysis implementation of Ensemble Filter Algorithm

(Whitaker et al. 2004, Compo et al. 2006, Compo et al. 2011)

Algorithm uses an ensemble of GCM runs to produce the weight **K** that varies with the atmospheric flow and the observation network every 6 hours

Using 56 member ensemble, HadISST1.1 prescribed SST and sea ice monthly boundary conditions (*Rayner et al. 2003*)

1871-2011: T62, 28 level NCEP GFS08ex atmosphere/land model

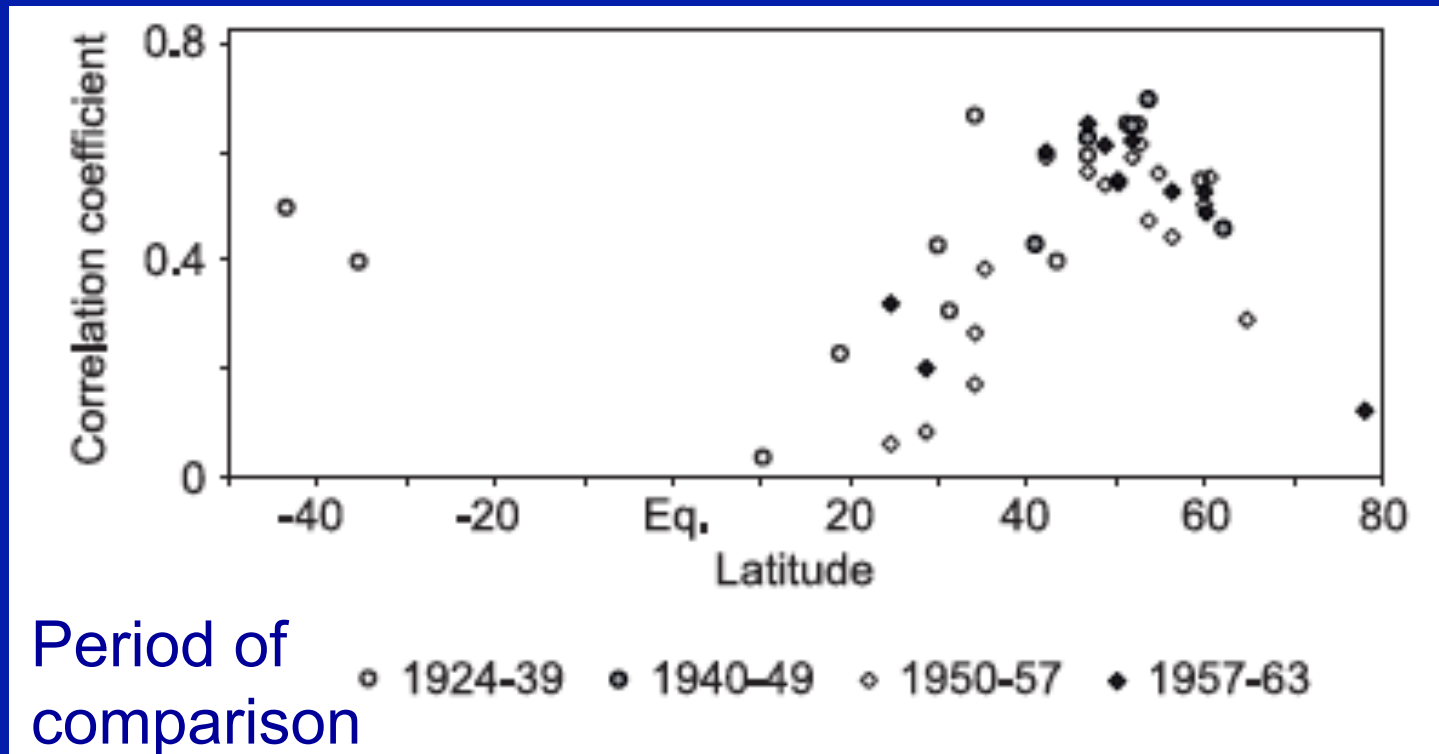
9 hour forecasts for 6 hour centered analysis window

- time-varying CO₂, solar and volcanic radiative forcing
- prognostic stratospheric ozone

Sampling and Model error parameterizations:

- Covariance localization (4000 km, 4 scale heights) and
- Latitude and time dependent multiplicative covariance inflation (alpha = 1.01 to 1.12) [*Anderson and Anderson, 1999; Houtekamer and Mitchell, 2001; Hamill et al. 2001; Whitaker et al., 2004*]

Column ozone from stations compared to 20CR



High correlations in Northern Hemisphere midlatitudes where dynamics are an important contributor to ozone variations. Correlations are consistent with measurements taken throughout the record.

[*\(Brönnimann and Compo 2012\)*](#)

Forecasts of Equatorial Stratospheric O₃ mixing ratios using US Navy NOGAPS-ALPHA model with and without CHEM2D-OPP temperature term (June)

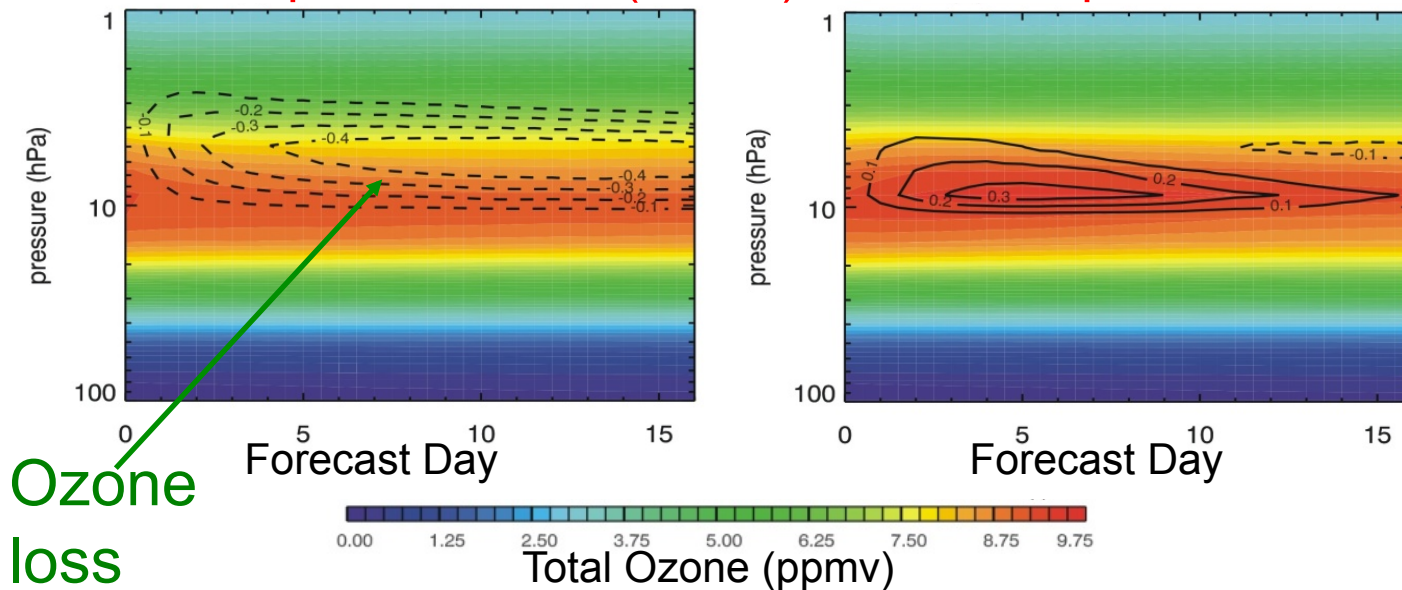
$$\frac{\partial \chi}{\partial t}(P-L) = (P-L)_0 + \frac{\partial(P-L)}{\partial \chi_{O_3}} \bigg|_0 (\chi_{O_3} - \bar{\chi}_{O_3}) + \frac{\partial(P-L)}{\partial T} \bigg|_0 (T - \bar{T})$$

Without temperature term (~GFS)

With temperature term

Shading:
Total O₃

Line
Contours
show O₃
tendency
from initial
condition
(dashed=
Loss)



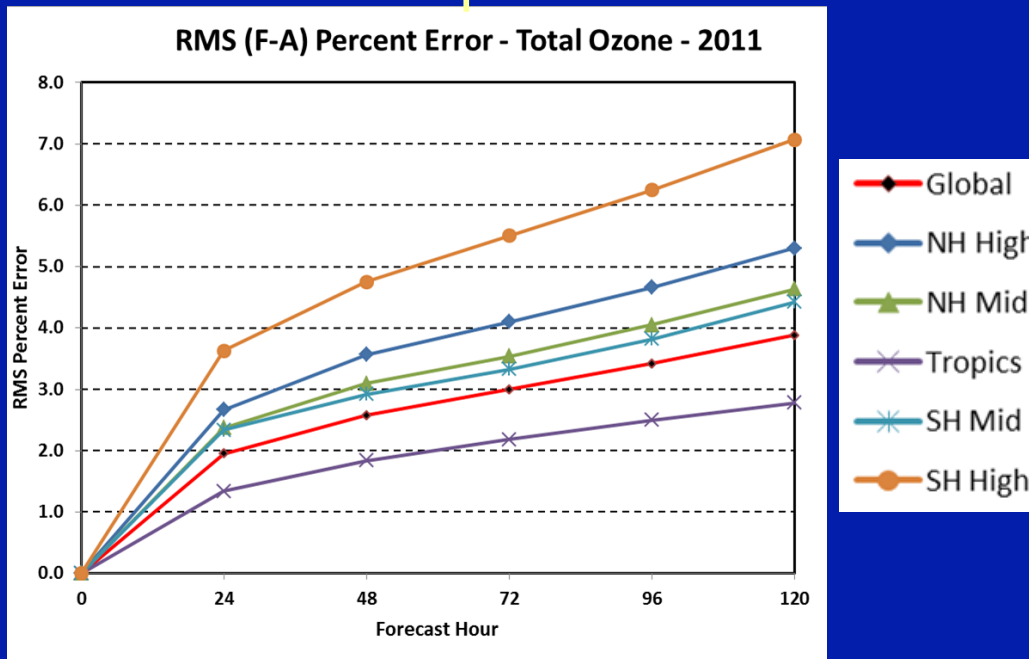
Adding temperature term should significantly reduce unrealistic loss in GFS-type implementation

χ_{O_3} prognostic Ozone mixing ratio
 T Temperature
 c_{O_3} column ozone

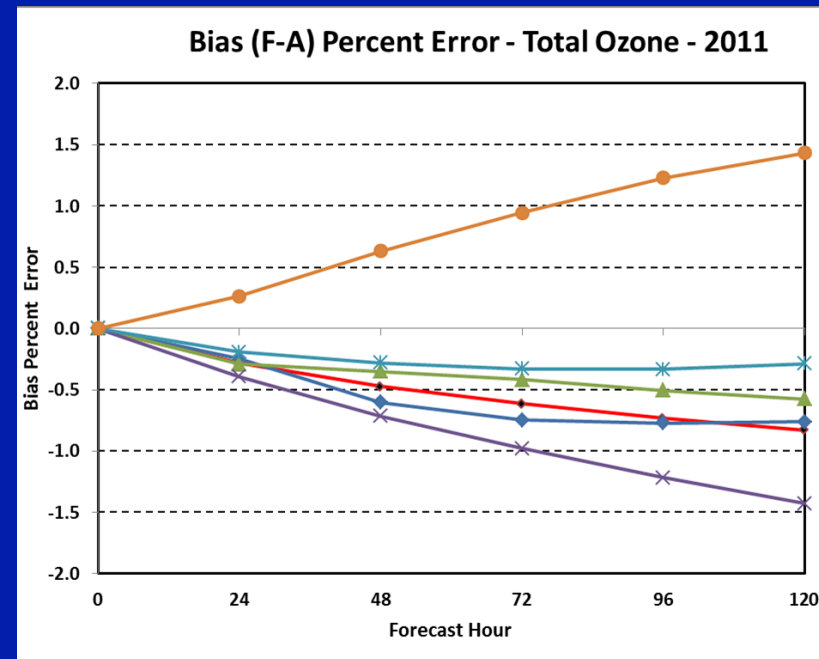
McCormack et al. 2013

GFS ozone forecast skill for 2011

Root Mean Square Error



Bias



GFS ozone forecast skill degrades significantly after 5 days due, in part, to unrealistic losses over most of the globe resulting in a global negative bias.

Why the loss of ozone? May be related to terms not used.

Long et al. 2013